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Concrete-filled steel tubes with reinforcing bars or angles under axial tension

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ABSTRACT

A series of tests on concrete-filled steel tubes (CFSTs) with reinforcing bars or angles under axial tension were conducted in this study. In total, thirteen full scale specimens having length of 4000 mm and outer diameter of 400 mm were tested. The steel tubes were fabricated from structural steel with nominal yield strength of 460 MPa and nominal plate thickness of 4 or 6 mm. Reinforcing bars or angles were placed inside the steel tube before the filling of concrete. The behaviour and strengths of CFSTs with reinforcing bars or angles under axial tension were investigated. The load-axial displacement curves and load-strain curves were obtained. The cracks in the core concrete were also investigated from the failure specimens. The tensile strengths are compared with the design strengths calculated using the current AISC standard. Design equations were proposed for the tensile strengths and elastic tensile stiffness of CFSTs with reinforcing bars or angles.

1. Introduction

Concrete-filled steel tubes have been widely used in civil engineering because of their excellent mechanical performance under compression. However, the axial tension force is the governing parameter in some cases, such as electronic transmission towers, as shown in Fig. 1. The area of steel tubes has been increased to resist the axial tensile force because the concrete has little contribution. However, steel tubes with large diameters have the problem of local buckling, whereas steel tubes with large thickness are difficult to fabricate and install. Therefore, concrete-filled steel tubes (CFSTs) with reinforcing bars or angles were considered.

Previous research mainly focused on the behaviour of CFST under compression [1–6], bending [7–11], or torsion [12–14]. There are few studies reported on the tensile behaviour of CFSTs. Han et al. [15] studied the behaviour of a CFST under axial tension based on small-scale test specimens. Experimental and numerical studies were conducted on the tensile behaviour of concrete-filled double skin steel tubular members by Li et al. [16–17]. Li et al. [18] also studied the behaviour of CFST eccentric tension. The behaviour of concrete-encased CFST members under axial tension was investigated by Han et al. [19]. There is a lack of studies on the tensile behaviour of CFSTs with reinforcing bars or angles. In addition, previous research studies are mainly conducted on small-scale specimens, which is not suitable for CFSTs with reinforcing bars or angles.

This paper is devoted to investigating the axial tensile characteristics of CFSTs with reinforcing bars or angles based on large size specimens. Full-scale test specimens were tested in this study. First, the diameter of the CFST should be large enough to contain the reinforcing bars or angles. Second, the length of the CFST should be long enough to develop bond strength between the steel and concrete. Special attention was placed herein to the utilization of reinforcing bar or angle inside. For very long CFST specimens such as used in electronic transmission towers, flange connection between steel tubes and the bolt connections between angles were used. Therefore, the effects of the flange connection between steel tubes and the bolt connections between angles were investigated. Finally, design equations are proposed for the tensile strengths and elastic tensile stiffness of CFSTs with reinforcing bars or angles.

2. Experimental investigation

2.1. Test specimens

The test specimens were fabricated by moulding a flat steel plate into a round shape, and then the ends of the steel tubes were cut to specified lengths of 4000 mm. There are two series of test specimens with nominal thicknesses of steel tube of 4 mm and 6 mm. The reinforcing bars or angles were placed inside the steel tubes before the filling of self-compacting concrete. There is no connection between the steel tubes and the reinforcing bars or angles. The self-compacting concrete was cured without any vibration. During curing, a very small amount of longitudinal shrinkage occurred at the top of the column. High-strength cement was used to fill this

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Nomenclature

A_c	cross-sectional area of concrete;
A_s	cross-sectional area of steel tube;
A_{sa}	cross-sectional area of angle;
A_{sr}	cross-sectional area of reinforcing bar;
D	outside diameter of steel tube;
d	diameter of reinforcing bar;
E	elastic modulus of steel;
E_c	elastic modulus of concrete;
E_s	elastic modulus of steel tube;
E_{sa}	elastic modulus of angle;
E_{sr}	elastic modulus of reinforcing bar;
$(EA)_T$	elastic tensile stiffness;
$(EA)_{T1}$	elastic tensile stiffness obtained from the load-axial displacement curve;
$(EA)_{T2}$	elastic tensile stiffness obtained from the load-strain curve;
$(EA)_{T\text{-}Pro}$	elastic tensile stiffness predicted using the proposed equation;
f_{cu}	compressive strength of concrete on 150 mm cubic;
f_t	tensile strength of concrete;
f_u	ultimate tensile strength of steel;
f_y	yield strength of steel;
f_{ysa}	yield strength of angle;
f_{ysr}	yield strength of reinforcing bar;
L	length of test specimen;
l	width of angle leg;
T	thickness of steel tube;
T_y	tensile strength;
$T_{y\text{-AISC}}$	tensile strength predicted using AISC standard;
$T_{y\text{-Test}}$	tensile strength of test specimen;
$T_{y\text{-Pro}}$	tensile strength predicted using the proposed equation;
t	thickness of angle;
α	steel ratio ($=A_s/A_c$);
δ	percentage elongation after fracture

longitudinal gap before the welding of the top steel end plate. Two 20-mm-thick steel plates were welded to both ends of the specimens to ensure full contact between the specimen and the end bearing. There are hoop and longitudinal ribs at both ends of the steel tube, as shown in Fig. 2. Details and dimensions of the end ribs are shown in Fig. 3(a) and (b), respectively. The end ribs are designed to enhance the load transfer ability between the steel tube and concrete.

Concrete-filled steel tubes with reinforcing bars or angles were tested in this study. Eight reinforcing bars with a nominal diameter of 16 mm or four equal angles with nominal size of 56 × 5 were placed inside the CFST. The layout of reinforcing bars and angles is shown in Fig. 2(a) and (b), respectively. Hollow steel tubes and concrete-filled steel tubes were also tested for comparison. In addition, specimens having flange connections between steel tubes and specimens having bolt connections between angles were tested to investigate the effects of connections. The flange connection and bolt connection are shown in Fig. 4(a) and (b), respectively.

The test specimens are labelled such that the type of specimen and nominal thickness of the steel tube can be identified from the label. The labels and the corresponding specimens are listed in Table 1. The last character "A" or "B" refers to repeated test specimens. The measured cross-section dimensions and specimen length for each test specimen are shown in Table 2.

2.2. Test setup

The test set-up is shown in Fig. 5. An 8000-kN hydraulic testing machine was used to apply axial tensile force to the specimens. Two spherical bearings were used at the upper and lower end bearings. Each spherical bearing was free to rotate in any direction. A small initial load of approximately 10% of design strength was applied on each specimen before testing to eliminate any possible gaps between the bearing plates and the bolts.

Eight strain gauges mounted on the specimen surface were installed at the mid-height to measure the longitudinal and transverse strains of the steel tube. For a specimen having a flange connection on the steel tube, strain gauges were mounted onto the bolts of the flange. The test results indicate that the tensile force is almost the same in all bolts. For the reinforcing bar and angle inside the concrete, there is no strain gauge attached to keep the interaction between the steel and concrete intact. Two LVDTs at each end of the test specimen were used to record the axial elongation. Displacement control was used to drive the hydraulic actuator at a constant speed of 1.0 mm/min for all test specimens. The use of displacement control allowed the tests to be continued into the post-ultimate range. A data acquisition system was used to record the applied load and the readings of the transducers at regular intervals during the tests. The test was stopped when the strain gauge reading at the mid-length reached 5000 $\mu\varepsilon$.

Coupon tests were performed to determine the tensile properties of the steel tubes, reinforcing bars, and angles. The measured average values of the Young's modulus (E_s), yield stress (f_y), ultimate tensile strength (f_u), and percentage elongation after fracture (δ) are shown in Table 3. The average cubic strength (f_{cu}), tensile strength (f_t), and elastic modulus (E_c) of concrete at 28 days were 61.6 MPa, 4.06 MPa, and 36,260 MPa, respectively. The tests were conducted from 28 days after the casting of the concrete.

3. Test results and discussion

3.1. Tensile load versus axial displacement curves

The tensile load versus axial displacement curves of hollow steel tube specimens, CFST specimens and CFST specimens with reinforcing bars or angles are compared in Figs. 6 and 7. The load versus axial displacement curve of all test specimens exhibits three stages: elastic, elastic-plastic and plastic stages. All test specimens have good ductility. The hollow steel tubes are shown to have the lowest strengths and elastic tensile stiffness. Because of the existence of the reinforcing bars or angles, both the tensile strength and elastic tensile stiffness of CFST specimens with reinforcing bars or angles are higher than those of the reference CFST specimens. Specimens having a flange connection between the steel tube (FC) or bolt connection between the angle (BC) have no increase in tensile strength relative to specimens without a connection. Specimens CFST-RB-FC-6 and CFST-AG-FC-4 exhibit an increase in elastic tensile stiffness compared with specimens CFST-RB-6 and CFST-AG-4, respectively. Specimen CFST-AG-BC-6 showed a significant reduction in elastic tensile stiffness compared with specimen CFST-AG-6. This may be caused by the slip at the bolt connection. The tangent line of the load versus axial displacement curve through the original point is used to calculate the elastic tensile stiffness $(EA)_{T1}$, as presented in Table 4.

3.2. Tensile load versus strain curves

For hollow steel tube specimens, CFST specimens, and CFST specimens with reinforcing bars or angles, the tensile load versus average longitudinal strain curves and tensile load versus average hoop strain curves are shown in Fig. 8(a) and (b), respectively. The negative value of average hoop strain indicates that the diameter of the steel tube is reduced under tensile loading. CFST specimens displayed less hoop